Title: Reduction of exposure to simulated respiratory aerosols using ventilation, physical distancing, and universal masking

Collection Methods

Environmental chamber and ventilation

The testing environment consisted of an environment chamber measuring 3.15 m × 3.15 m × 2.26 m (gross internal volume of 23.8 m^3). An internal re-circulating high-efficiency particulate air (HEPA) filtration system (Flow Sciences, Inc.) was used to reduce background aerosol particle concentrations to near-zero prior to each experiment. The HEPA system consisted of a 10.8 cm return duct positioned along the left wall 55.9 cm from the ground leading to the central motor/filter unit and a supply duct positioned along the right wall at a height of 2.19 m from the floor. No external fresh air was introduced into the environmental chamber during experimentation. The HEPA system was configured for dilution ventilation for our experiments in order to maximize the removal of aerosol particles from the test chamber. Six Grimm 1.108 optical particle counters (OPCs; GRIMM Aerosol Technik Ainring GmbH & Co. KG) were positioned at a height of 152 cm throughout the chamber. The OPCs measured particle concentrations from 0.3 to 3.0 μm at a frequency of 1 Hz, except for one OPC sampler at 0.167 Hz. Four OPCs were affixed to telescopic stands 152 cm above the floor and referred to as "area samplers." One OPC was positioned 3.2 cm next to the mouth central axis and anteriorly planar to the mouth opening of the recipient simulator (see below) and fit behind a mask affixed to the simulator; this position is denoted as "at the mouth of the breather" for presentation purposes. The remaining OPC was positioned 8.9 cm next to the mouth central axis and anteriorly planar to the mouth opening of the recipient simulator to allow for measurement in the personal breathing zone outside of a mask affixed to the simulator. All OPCs were controlled and data was logged using a custom program in LabVIEW v. 2009 (National Instruments).

In addition to particle removal, the HEPA system provided ventilation, with a variable transformer (Staco Energy Products, Co.) used to set the HEPA system flow rate. Air exchange rates were determined via single-point measurement of the linear air flow at the return duct using a Model 5725 VelociCalc rotating vane anemometer (TSI, Inc.) equipped with a tapered air cone (TSI, Inc.). The return duct was straightened for a length of >10 diameters from the return opening to minimize turbulent flow during anemometer readings for air changes per hour (ACH) derivation. The HEPA system was set to 0 ACH, 4 ACH (0.255 m^3/s flow), 6 ACH (0.382 m^3/s), and 12 ACH (0.765 m^3/s); calculations assumed zero leakage into the chamber. Effective air filtration rates were derived empirically. Briefly, a 1% NaCl solution was nebulized using an aerosol generator (Model 8026, TSI) until the 0.3–0.4 μm particle size channel reached 105 particles per liter under constant mixing using a household fan. After a 15-min mixing period, the HEPA filtration system was set to the desired ACH based on anemometer measurements. Particle concentrations were measured for 20 min using five of the six OPCs to derive particle exponential decay curves spatially throughout the chamber. Theoretical particle exponential decay curves were modeled from the three smallest size bins (0.3–0.4 μm, 0.4–0.5 μm, and 0.5–

0.65 μm) assuming negligible loss to chamber surfaces and aerosol agglomeration using MATLAB v. 9.6 (Mathworks). The slope of the modeled particle decay was assumed to be first order as per equation:

$$CC_{tt} = CC_{ii}ee^{\lambda ltt}$$

Where:

C_t is the particle concentration at time t (#/cm^3)
C_i is the initial particle concentration at time zero (#/cm^3)
e is Euler's number, approximated to 2.71828
λ is the slope of particle concentration change over the time (#/cm^3/second)
t is time (seconds)

Empirical concentrations of particles measured by the five area OPCs were then fitted via log-linear regression and the resultant decay coefficient (λ) derived to estimate the effective OPC-specific ACH.

Aerosol source and simulators

The source simulator had a head form with pliable skin (Hanson Robotics). For these tests, a single cough and two versions of simulated breathing were examined. The simulated respiratory aerosol particles were produced with a 14% w/v KCl solution nebulized by a single jet Collison atomizer (BGI, Inc.) with an inlet pressure of 103 kPa (15 lbs./in2) prior to passive drying (Model 3062; TSI, Inc.), dilution with dry filtered air at 10 L/min (single cough tests) or 15 L/min (breathing tests), and neutralization by an ionizer (Model HPX-1, Electrostatics, Inc.). The coughing modality was performed by loading the simulator elastomeric bellows with test aerosol, followed by a single 4.2 L rapid exhalation at a peak flow rate of 11 L/ min; the simulator did not breathe following the cough. For breathing tests, the simulator breathing rate was 12 breaths/min with a tidal volume of 1.25 L and ventilation rate of 15 L/min. The breathing parameters correspond to the ISO standard for females performing light work. For the breathing modality, the nebulizer was cycled 10 s on and 50 s off continuously throughout the test duration. Tests were conducted for a duration of 15 min, except for a limited subset of testing conditions which were conducted for 60 min. As an additional examination of the time dependency of ventilation in reducing recipient exposure, additional tests were conducted using a modified aerosol generation cadence during the breathing action. During these tests, the nebulizer generated aerosol continuously for the first 3 min of the test, after which the nebulizer was turned off, and are henceforth designated short-term aerosol generation tests.

To simulate source aerosol exposure to a recipient, a breathing simulator (Warwick Technologies Ltd.) with a pliable skin head form (Respirator Testing Head Form 1—Static; Crawley Creatures Ltd.) was placed upon a mobile cart to enable alteration of the distance between source and the recipient. The mouth of the recipient simulator head form was positioned 152 cm above the floor. The simulator breathed with a sinusoidal waveform at 21.5 breaths/min with a ventilation rate of 27 L/min. These parameters are approximately the average of the ISO standards for males

and females performing moderate work. Both simulators were controlled during all experiments using custom scripted programs in LabVIEW.

Experimental procedure

For experimental trials with masking conditions, a 3-ply cotton mask (Hanes Defender, HanesBrand, Inc.) was fitted to the respective simulator followed by fit factor assessment using the PortaCount Pro+ (TSI, Inc.) in the N95 mode (measuring negatively charged particles 55 nm in diameter) as per manufacturer's instructions. A daily quality assurance test was conducted using the 3M 1860 N95 respirator (Saint Paul, MN). To test the effect of layering aerosol mitigation strategies of universal masking, physical distancing, and ventilation, experiments consisting of a matrix of the three variables were conducted (Table 1). For masking, the combinations of no masking (neither simulator wore a mask) and universal masking (both simulators wore a 3-ply cotton mask) were examined. For physical distancing, given the limitation of the distance due to the size of the environmental chamber, 0.9 and 1.8 m distances were examined. For ventilation, four ACH rates were selected: 0, 4, 6, and 12. After mask fitting and distance configuration, the environmental chamber was sealed, and the HEPA filtration system run at maximal rate to minimize background airborne particles. Thereafter, the HEPA filtration system was either turned off (0 ACH) or set to the desired air exchange rate (4–12 ACH) and allowed to run for 15 min, during which time all OPCs were initialized to begin particle concentration data collection and the recipient simulator activated to begin breathing. After the air exchange stabilized, the source simulator was initiated to cough or breathe, and aerosol concentrations were measured for 15 min. The chamber was allowed to cool to 22 °C between experiments to reduce the inter-test temperature variability. Three independent experimental replicates were conducted for each unique experimental condition without condition randomization.

Table 1. Experimental Parameters

Aerosol Generation Modality	*Test Duration (minutes)*	*Physical Distance (m)*	*Ventilation Air Changes per Hour*	*Masking*	*Nebulizer and Simulator*
Cough	15	0.9 and 1.8	0, 4, 6, 12	No masks and universal masking	Nebulizer active during pre-cough inspiration and inactive for remainder of experiment.
Breathing	15	0.9 and 1.8	0, 4, 6, 12	No masks and universal masking	Nebulizer active 10 seconds/inactive 50 seconds through duration of testing.
Breathing	60	1.8	0, 4, 12	No masks and universal masking	Nebulizer active 10 seconds/inactive 50 seconds through duration of testing.